Nonlinear Characterizing of the Crack Growth Behavior in a Filled Elastomer

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Abstract:

In this study, the crack growth behavior in a filled elastomer, containing hard particles embedded in a rubbery matrix, was investigated. The specimen was tested at a constant strain rate of 0.067 cm/cm/min at room temperature. Two initial crack lengths, 2.54 mm and 12.7 mm, were considered. A hybrid experimental-numerical method was used to calculate the J-integral value. They also revealed that the initial crack length had a significant effect on the critical J-integral value for the onset of crack growth but had no significant effect on the subsequent crack growth behavior. It also revealed that a power law relationship existed between the crack growth rate and the J-integral.

Introduction:

An important engineering problem in structural design is the evaluation of structural integrity and reliability. There are two well-known structural design philosophies; namely, safe-life and damage-tolerance. According to the safe-life design philosophy, no crack will initiate in the structure during its design service life. In other words, the service life of a structure is terminated once a crack is predicted or detected. On the other hand, the damage-tolerance design philosophy assumes the existence of cracks or defects in the structures and guards against their unstable growth. Meaning that the damage-tolerance design approach seeks to avoid the growth of the existing crack to a critical crack size. Therefore, in order to determine the ultimate service of a structure or the critical crack size, a crack growth model needs to be developed.
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In recent years, a considerable amount of work has been done studying crack growth behavior in particulate composite materials under different loading conditions (1-6). Experimental findings indicate that power law relationships exist between the crack growth rate, da/dt, and the Mode I stress intensity factor, K_I. These experimental findings support the theory developed by Knauss (7) and Schapery (8) in their studies of crack growth behavior in linear viscoelastic materials. Classical fracture mechanics principles, especially linear elastic fracture mechanics, are well established for single-phase materials. Experimental data indicate that linear fracture mechanics theories are applied to the particulate composite materials with varying degree of success. However, there has been relatively little effort in characterizing the crack growth behavior in highly filled elastomers based on nonlinear fracture mechanics.

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14. ABSTRACT
In this study, the crack growth behavior in a filled elastomer, containing hard particles embedded in a rubbery matrix, was investigated. The specimen was tested at a constant strain rate of 0.067 cm/cm/min at room temperature. Two initial crack lengths, 2.54 mm and 12.7 mm, were considered. A hybrid experimental-numerical method was used to calculate the J-integral value. They also revealed that the initial crack length had a significant effect on the critical J-integral value for the onset of crack growth but had no significant effect on the subsequent crack growth behavior. It also revealed that a power law relationship existed between the crack growth rate and the J-integral.

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In this study, edge-cracked sheet specimens were used to characterize the crack growth behavior in a highly filled elastomer at a constant strain rate of 0.067cm/cm/min. The specimens were made of a highly filled elastomer containing hard particles in a rubber matrix. A crack was cut at the middle of the edge of the specimen with a razor blade (Fig.1). Two initial crack lengths, 2.54 mm and 12.7 mm, were considered. A hybrid method, consisting of experimental and numerical analyses, was used to determine the J-integral as a function of the applied strain. The crack growth rate was calculated by the secant method. The experimental data were analyzed to determine the effect of the material's microstructure on the crack growth behavior, the strain fields, and the functional relationship between the crack growth rate and the J-integral.

The Experiments

In this study, a single-edge notched specimen was used to determine the local behavior near the crack tip under a constant strain rate condition at room temperature. Prior to testing, the specimen was conditioned at the test temperature for 1 hour, and loaded in a straining stage. A stepping motor was used to power the straining stage and to control the rate of deformation. To position the crack tip, a positioning stage was used to move the specimen in the x and y directions. The positioning stage was controlled by operating a joystick device. The instruments used to visualize the deformation and fracture processes were a Nikon Metallurgical microscope, a CCD camera, and a personal computer with a frame grabber unit

To determine the strain fields near the crack tip, a Large Deformation Image Correlation (LDDIC) program, developed by Vendroux & Knauss (9) and Gonzalez (10) was used. The LDDIC program was developed by modifying a Digital Image Correlation (DIC) program developed by Sutton al.et. (11) for small deformations. The problem in applying DIC to compute strain fields in a large deformation process is the failure of convergence of the DIC algorithm if the strain is larger than 10%. To circumvent this problem, the LDDIC takes intermediate images (or steps) of the deformation between the undeformed and the deformed states of the deformation, and, then, computes the displacements and the displacement gradients for every step of the deformation. The intermediate results are combined to produce the displacements and displacement gradients for the global deformation. To determine the accuracy of the LDDIC program, a test was conducted on a specimen made of a homogeneous silicone rubber and coated with microscopic speckles. The specimen was stretched to 80% strain. A sequence of 15 images was taken during the deformation process and the strains were calculated by the LDDIC program. A comparison of the prescribed and calculated strains showed that a maximum deviation of 1% strain occured at the 40% strain level. This experimental result validated the LDDIC method.

A J-intergal computer program was written and incorporated in a finite element computer code (FEAP). The accuracy of the J-integral program was checked by calculating the J-integral for a given HRR field associated with a known J-integral value. The result indicates that the calculated and the predicted J-integral values differ by 3%. The path-independent nature was checked by computing the J-integral values along 9 different rectangular paths. The closest path to the crack tip was 1.9mm from the crack tip whereas the farthest one was

5.3 mm from the crack tip. The results indicate that the variation of the computed J-integral values along different paths is within 1%.

The crack growth rates, da/dt, as a function of time were calculated. In calculating da/dt, the secant method was used. In the secant method, the crack growth rate is computed by calculating the slope of a straight line connecting two adjacent a versus t data points. The calculated average crack growth rate is assigned at a point midway between each pair of data points.

Results and Discussion:

When a crack occurs, the high stress at the crack tip will induce high damage near the crack tip region. The high damage zone at the crack tip is defined as the failure process zone, which is a key parameter in viscoelastic fracture mechanics. Experimental data reveal that when the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not necessarily formed in the immediate neighborhood of the crack tip. The formation of the voids is not restricted to the surface of the specimen where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids or damage zones will be generated in the specimen's interior. Consequently, there are a large number of strands, which separate the voids and are essentially made of the binder material, that form inside the failure process zone. These damage processes are time-dependent and are the main factor responsible for the time-sensitivity of strength degradation as well as fracture behavior of the material.

Figure 2 shows a typical set of photographs showing the crack surface profile during opening and growth of a crack in the composite material specimen. Experimental data show that crack tip blunting occurs both before and after crack growth (Fig. 2). Due to the heterogeneous nature of the composite material, the degree of blunting varies with the position of the advancing crack tip. This suggests that the local microstructure near the crack tip plays a significant role in the blunting phenomenon. During the blunting stage, voids developed in the failure process zone (Fig.2a). The failure of the material between the void and the crack tip leads the crack to grow a short distance. In other words, the coalescence of the void and the crack tip leads the crack to grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the failure process zone tip. When this occurs, the crack tip resharpens temporarily (Fig.2b). Thus, the process consists of a blunt-growth-blunt phenomenon which is highly nonlinear. Referring back to Fig.2, a close look at the crack tip region reveals that the failure process zone has a cusp shape which is consistent with that predicted by Schapery (8) in his study of fracture of viscoelastic material. In the failure process zone, the material can be highly nonlinear and suffer extensive damage. Experimental data indicate that the direction of the failure process zone with respect to the crack plane varies from specimen to specimen. This is believed to be related to the size of the highly strain region as well as the local microstructure of the material in that region. For a large magnitude of tip blunting, the size of the highly strained region is also large. Therefore, depending on the local microstructure, the direction of the failure process zone shows a relatively large variation. Experimental results reveal that before crack growth, the

failure process zone develops either above, below, or along the crack plane. After crack growth, the successively developed failure zones at the tip of the propagation crack undulate about the crack plane, resulting in a zig-zag shape of crack growth. It is interesting and important to note that the crack has a tendency to grow in the average direction perpendicular to the applied load direction. The change of the stress concentration location as the result of crack tip blunting also contributes to the variation in failure process zone direction. When the crack tip is extensively blunted, the stress concentration location changes from the tip of the sharp crack to the upper and lower corners of the blunted crack. Therefore, the probability of developing a failure process zone near the corners of the blunted crack is greater.

In the above paragraphs, we discussed the damage mechanisms and the local fracture behavior in the immediate neighborhood of the crack tip. In the following paragraphs, the effect of microstructure on the strain distributions near the crack tip and the crack growth behavior are discussed.

Experimental findings reveal that the strain fields are highly nonhomogeneous and high strain regions are localized in the neighborhood of the crack tip. Figure 3 shows the normal strain distributions along the crack plane as a function of the far field strain (FFS). It is interesting to note that the high strain region is localized near the crack tip, and it covers a region about 0.5mm from the crack tip. The strain outside the high strain region is approximately equal to the far field applied strain.

A plot of J-integral values as a function of the applied strain is shown in Fig. 4. It is noted that the initial crack length has a significant effect on the J-integral versus the applied strain curves. In general, the rate of change of the J-integral value per unit of the applied strain level increases significantly when the applied strain is high. Figure 4 also shows that the critical applied strain levels for the onset of crack growth, as marked in Fig.4, for a_o equal to 12.7 mm case is significantly lower than that for a_0 equal to 2.54 mm case The averaged critical J-integral valves for the onset of crack growth are 542 Pa m and 225 Pa m for a_o equal to 12.7 mm and 2.64 mm, respectively. The crack growth resistance curves, plotting the J-integral value versus the crack growth increment, are shown in Fig. 5. It is noted that a considerable amount of stable crack growth takes place before the unstable crack growth occurs. The J-integral values corresponding to the unstable crack growth is significantly higher than that corresponding to the onset of crack growth.

A plot of J-integral value versus crack growth rate is shown in Fig. 6. According to Fig. 6, the variation of crack growth rate for the two initial crack length cases are within the scatter of the experimental data. Therefore, on the first approximation, it is assumed that the initial crack length has no effect on the crack growth behavior, and a single power law crack growth model, relating Log da/dt and Log J, can be used to describe the crack growth behavior in the material. Mathematically, it can be represented as

$$da/dt = b\, J^{C}$$

where b and c are constants.

Conclusions:

In this study, the crack growth behavior in a filled elastomer was investigated, and the relationship between the crack growth rate and the J-integral was determined. The crack growth rate was calculated by the secant method whereas the J-integral value was calculated by a hybrid experimental-numerical method. Experimental findings revealed that the initial crack length had a significant effect on the critical J-integral value for the onset of crack growth but had no significant effect on the subsequent crack growth behavior. It also revealed that a considerable amount of stable crack growth took place before the crack growth behavior became unstable. The critical J-integral value for the unstable crack growth is significantly higher than that for the onset of crack growth. In addition, a power law exists between the crack growth rate and the J-integral.

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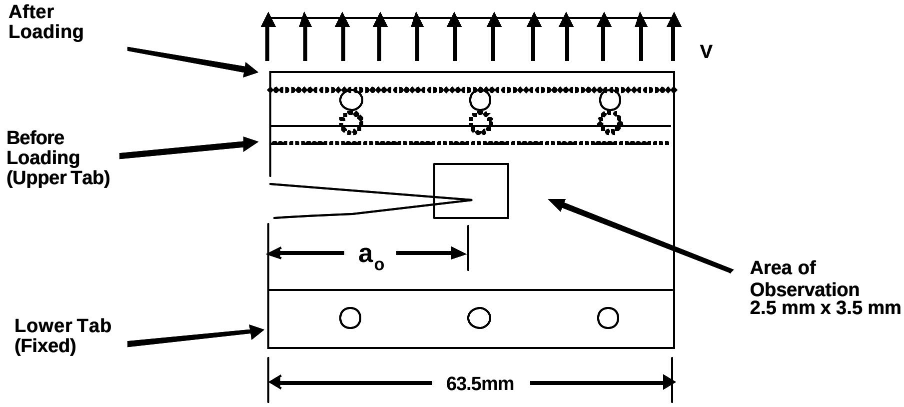
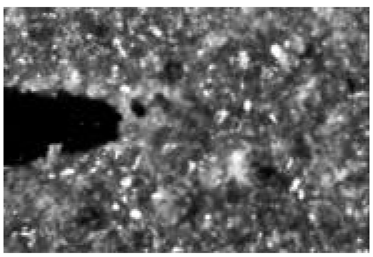
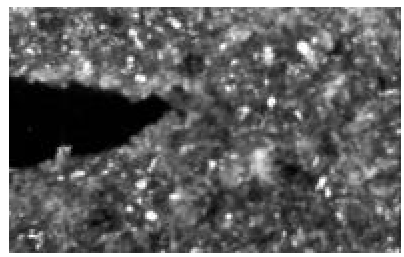


Fig. 1 Specimen Geometry.



(a)



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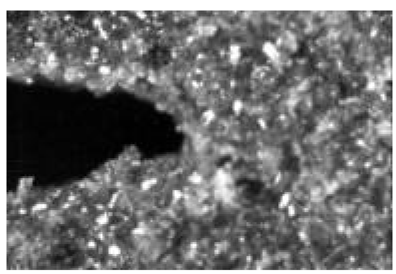

(c)

Fig.2 Crack Tip Profiles.

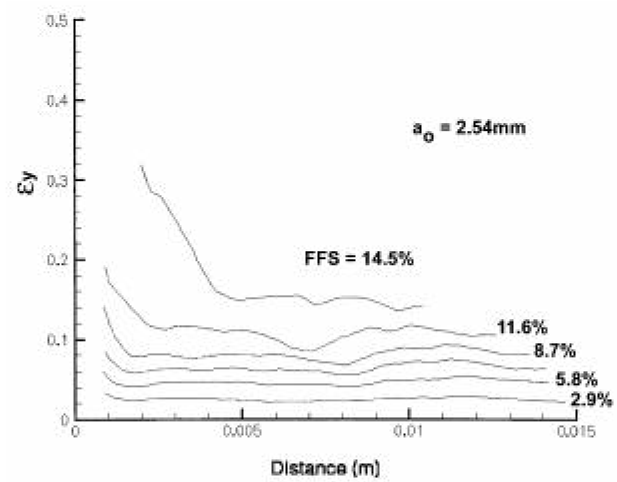

Fig.3 Normal Strain Distributions along the Crack Plane.

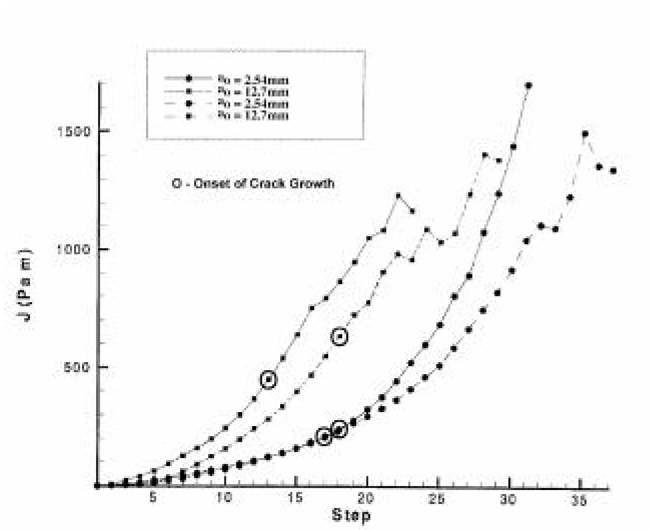

Fig.4 J-Integral versus Step.

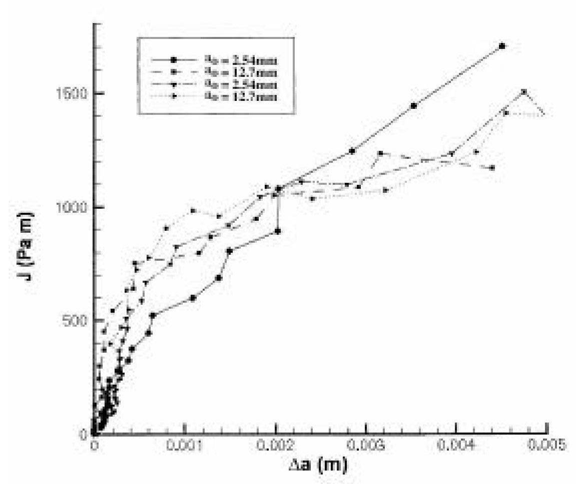

Fig. 5 Crack Growth Resistance Curves.

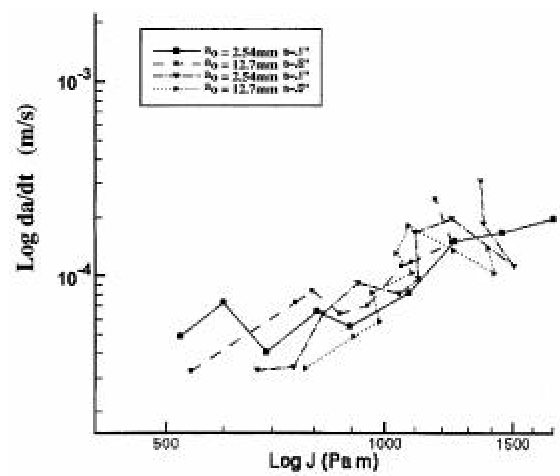

Fig. 6 Crack Growth Rate versus J-Integral.